DEVELOPMENT OF AN EMERGENCY CONTROL ALGORITHM FOR A FAIL-SAFE SYSTEM IN AUTOMATED DRIVING VEHICLES

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ABSTRACT

This paper proposes the concept of automated driving vehicle failsafe system structure. It contains vehicle hardware and software structure design for automated driving vehicle failsafe system. Moreover, it handles the contents fail detection, fault-tolerant control, and emergency braking strategy in case there is no driver intervention in the fail condition of automated driving vehicle. According to the 2017 'AUTOMATED DRIVE SYSTEM 2.0: a vision for safety' report released by the NHTSA, it states that deployment of the crash avoidance system is essential to switch to a minimum hazardous condition in the event of a problem with the self-driving vehicle, or the system cannot operate safely. First, the method used to build the hardware & software of the vehicle was based on the guideline of 'AUTOMATED DRIVE SYSTEM 2.0: Section 1 fallback (Minimal Risk condition)' report released by NHTSA. Second, a method of an algorithm is sliding mode control based fault tolerant control and emergency deceleration control which designed to target SAE International standard J3016 autonomous driving phase 4: automated driving system perform ass aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene. In this paper, to meet the requirements of autonomous driving phase proposed by SAE International standard J3016 phase 4 and NHTSA safety standard, the hardware configuration was created to ensure that the automated driving vehicle could perform the given task without proper driver intervention. In detection part, hardware (Actuator, Sensor, CAN signal, Upper&Lower controller) and module based failsafe diagnosis method and algorithm were proposed to detect fail condition. In decision and control part, when a failure of an automated driving vehicle is diagnosed, and no driver intervention was detected, the automated driving vehicle failsafe phase is a move to the system error. In the phase of the system error (lower controller), proposed methodologies are utilized. Automated driving vehicle experiments have demonstrated the algorithms as mentioned earlier and failsafe structure. First of all, it is true that not many papers and studies have been done on the failsafe system of an automated driving vehicle. NHTSA's safety report of an autonomous vehicle only contains a "suggestion" that says, "It is a good thing to do this," and has not yet created a rule. However, this paper proposes an automated driving vehicle failsafe system that is not commercialized but has been configured to meet NHTSA's requirements to take into account safety. The proposed failsafe system is applied to the automated driving vehicle, and the vehicle experiment was completed with the proposed algorithm. The proposed system is considered to be very compatible with the subject of the technical session by suggesting the system that meets the NHTSA standards as well as testing control and emergency systems targeted automated driving vehicle phase 4.

INTRODUCTION

Autonomous vehicle research aspect of failsafe and a fallback system is a very necessary and important study. Autonomous vehicles are composed of various sensors, computers, actuators and other types of equipment, and these equipment are configured to communicate together. In terms of fault diagnosis, each of them also needs real-time monitoring and also needs maneuver to be configured in the event of a failure. The algorithm proposed in this paper is an algorithm in the control part that makes an emergency stop when the fault is determined by fault diagnosis system when there is no driver intervention. The control classification was divided into two control categories, longitudinal control, and lateral control. Even if an error occurs that vehicle does not receive normal data from the upper controller that designed to recognition and judgment components of the autonomous driving system, the proposed algorithm only uses the vehicle's chassis information to provide a way for autonomous vehicles to respond safely. The vehicle hardware configuration is divided into upper controllers that responsible for recognition and judgment part and lower controller responsible for control of a vehicle. The lower controller consists of very robust hardware that allows for the safe longitudinal and lateral control in the event of errors in the upper controller.

Therefore, during the autonomous driving phase proposed by SAE International, level 4 suggests: the driving mode-specific performance by an automated driving system complete driving task, even if a human driver does not respond appropriately to a request to intervene.

Figure1. Waymo vehicle redundant Safety-Critical Systems. [1]

The hardware configuration was configured so that the autonomous vehicle could perform the failsafe system task without proper driver intervention. Although there are not many prior studies on the fault diagnosis system of autonomous driving systems was completed, the development of the failure diagnosis system of non-automated vehicles has already been carried out in terms of the failsafe system. YH.J developed the vehicle sensor fault diagnosis and acceptance algorithm and conducted the residual and adaptive threshold fault diagnosis without additional hardware. [3] KS. O conducted a study on the predictive fault diagnosis algorithm using sliding mode observers. [4] Advanced research in failsafe and system construction methods was consulted by overseas automotive OEMs. Google Waymo self-driving vehicles have applied fallback systems. Figure1. is Waymo safety-critical system description. Waymo vehicle's redundant system composed of backup computing, backup braking, backup steering, and a backup power system. [1] Similar to Google Waymo, CRUISE has a backup computer, backup actuator, signal communication redundant and data accumulation system. [2]

HARDWARE-BASED FAIL DETECTION CLASSIFICATION

In this chapter, mainly introduce module based classification of an autonomous vehicle fail detection and maneuver system. Hardware divide into Actuator, Sensor, Upper controller, CAN network and Lower controller. Actuator classifies as steering and throttle/brake. Sensor part composed of Lidar, Radar, and Vision (mono camera). The upper controller contains logic for perception and judgment of entire autonomous driving algorithms and calculates at regular intervals and transmits the calculated values to the lower-controller over real-time communication. CAN communication refers to the overall communication of the vehicle, including many sensors and actuators, vehicle inter communication, and uses a method to conduct real-time monitoring of their values. The Lower Controller consists of algorithms that calculate the relative sub-controller of the overall configuration, the algorithm for path tracking, or the control input that enters longitudinal control in the event of failure.

Sensor fail detection

The hardware fault detection method of the sensor is shown as Figure2. The manufacturer sends a corresponding fault signal from the sensor itself in the event of a fail. Delphi's radar has signals that can find many faults such as sensor communication error, sensor status failed, status blocked, and status over temperature, etc. Communication settings allow users to read the appropriate information. The figure 2. b) is about Ibeo LUX Ridar error and warning messages. Error contents internal error, a motor error, temperature rise, data loss, internal communication error, incorrect scan data, etc. The warning signal that is sent to the user can receive error messages such as internal communication, temperature increase, etc.

4E0	CAN_TX_COMM_ERROR	Indication that the sensor has detected a communication error	False/True	bool	0: False 1: True	False	50ms	MMR
4E1	CAN_TX_XCVR_OPERATIONAL	Sensor Status Radiating 0 = not radiating 1 = radiating	0 to 1	n/a	1	0	50ms	MMR
4E1	CAN_TX_INTERNAL_ERROR	Sensor Status Failed 0 = not failed 1 = failed	0 to 1	n/a	1	0	50ms	MMR
4E1	CAN_TX_RANGE_PERF_ERROR	Sensor Status Blocked 0 = not blocked 1 = blocked	0 to 1	n/a	1	0	50ms	MMR

6.1 Error register 1

Bytes	LUX error	Description	Comment
Bit 0	E-SP	internal error	contact support
Bit 1	E-Motor_1	motor fault	contact support
Bit 2	E-Buffer_1	scan buffer transmitted incompletely	decrease scan resolution/frequency/range; contact support
Bit 3	E-Buffer_2	Scan buffer overflow	decrease scan resolution/frequency/range; contact support
Bit 4	E-Meas_1	APD voltage failed	contact support
Bit 5		reserved	
Bit 6		reserved	
Bit 7		reserved	
Bit8…9	E-Temp	Bit 9: APD Over Temperature Bit 8: APD Under Temperature Bit 8 and 9: APD Temperature Sensor defect	provide cooling provide heating contact support
Bit 10	E-Motor_2	motor fault	contact support
Bit 11	E-Motor_3	motor fault	contact support
Bit 12	E-Motor_4	motor fault	contact support
Bit 13	E-Motor_5	motor fault	contact support
Bit14…15		reserved	

6.2 Error register 2

Bytes	LUX error	Description	Comment
Bit 0	E-IF_internal_1	no scan data received.	contact support
Bit 1	E-IF_internal_2	internal communication error	contact support
Bit 2	E-IF_internal_3	incorrect scan data	contact support
Bit 3	E-Configuration_1	FPGA not configurable	contact support
Bit 4	E-Configuartion_2	incorrect configuration data	load correct configuration values
Bit 5	E-Configuration_3	configuration contains incorrect parameters	load correct configuration values
Bit 6	E-Timeout_1	data processing timeout	decrease scan resolution or scan frequency
Bit 7	E-Timeout_2	reset the computation of the environmental model	contact support
Bit8…15	reserved		

6.3 Warning register 1

Bytes	LUX warning	Description	Comment
Bit0	W-CMD	internal communication error	
Bit1	W-Range_1	internal warning	
Bit2	W-Range_2	internal warning	
Bit3	W-low_temperature	temperature too low	warning of insufficient temperature
Bit4	W-high_temperature	temperature too high	warning of exceeding temperature
Bit5	W-Motor_1	internal warning	
Bit6	W-Motor_2	internal warning	
Bit 7	W-Sync	synchronization error	check synchronization- and scan frequency
Bit7…15	RES 7…15	reserved	

6.4 Warning register 2

Bytes	LUX warning	Description	Comment
Bit0	W-IF_CAN	CAN Interface blocked	check CAN bus and CAN connection
Bit1	E-IF_ETH	Ethernet Interface blocked	check Ethernet connection
Bit2	W-CANdata	incorrect CAN message received	check CAN data
Bit3	W-IF_internal_1	incorrect scan data	contact support
Bit4	W-ETHdata	unknown or incomplete data	check Ethernet data
Bit5	W-Command	incorrect or forbidden command received	check command
Bit6	W-Flash	memory access failure	restart ibeo LUX, contact support
Bit7	W-Overflow_1	internal overflow	contact support
Bit8	W-EgoMotion	vehicle data update missing	check CAN vehicle data
Bit9	W-Mounting Position	incorrect mounting parameters	correct mounting position according to OM
Bit10	W-CalcFrequency	no object computation due to scan frequency.	set the scan frequency to 12.5 Hz to receive objects
Bit11…15	reserved		

Figure2. a) Delphi Radar error message b) Lidar IBEO LUX error message[13]

Communication & controller fail detection

Inside the vehicle, communication is via the CAN bus (Controller Area Network) communication protocol is a standard communication specification designed to enable multiple devices to communicate with each other without a host computer. In order to detect errors in CAN signals, it is important to identify characteristics of CAN signals. Using the characteristics that the last value in the event of CAN failure is maintained by the host controller, utilized PC LabVIEW signal processing program, which is a higher control of an autonomous vehicle, can recognize an error about a CAN state that is judged to be a CAN error when the same value is received. The LabVIEW program itself can also detect errors on the CAN signal using a virtual instrument (VI) that detect for CAN errors. VI could find an error where the internal CAN state value is fixed. The upper controller refers to a PC and the lower controller (micro-autobox) that is responsible for control. Fault finding system that recognizes if one system fails while the PC to autobox system sends and receives data over CAN communication in real time.

FAILSAFE CONTROL

In this chapter, mainly address concept of failsafe control and reason of study. The main purpose of this part is to meet the requirements of SAE International level 4 as figure3. the control part that makes an emergency stop when there is no driver intervention after the failure determined by the algorithm.

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure3. SAE International standard J3016, Levels of vehicle automation

Failsafe control description The control part is divided into the longitudinal and the lateral part. Offer a way for autonomous vehicles to respond safely, using the vehicle's chassis information only, even if there is no information on the upper control part, i.e., the recognition and judgment part. The system error situation defined in this paper means network communication is blocked. In this situation, the last value in CAN network is only useful information. A failsafe module proposed in this paper utilized the unique phenomenon of system error and used that useful information to predict and control. System error – supervisor part contains prediction contents. The method used for longitudinal control is to calculate the safe driving distance in real time and transmit to reference deceleration model, and reference model calculates reference distance and reference velocity model for sliding mode control based deceleration and stop the algorithm. It is possible to make a stop within a safe distance through the above method. Lateral control consists of an algorithm that only uses the vehicle chassis information. This algorithm uses last information (desired path) of the upper controller to follow the path using DR to the lateral control algorithm.

The entire module was composed of the failure detection part that finds the failure of the total module, the failure detection part that carries out the classification for the failure, and the control model that is responsible for controlling deceleration with limited information.

Figure4 is hardware concept of the autonomous vehicle including the failsafe module. Considering autonomous vehicle hardware structure, the failsafe module was configured under normal circumstances, the algorithms of the perception, decision, and control algorithm operating in the upper controller. In order to prepare for a fault situation, the algorithms of the prediction in a fail-safe module using information from the upper controller calculate prediction algorithm in real-time. If an error is detected by the error-diagnosis module and no driver intervention is determined, the final information is used to predict and control. The last safety distance (in normal situation information) received from the upper controller is used in two ways. In the lateral direction, the dead reckoning algorithm will be used to drive the safety path, and in the longitudinal direction, sliding

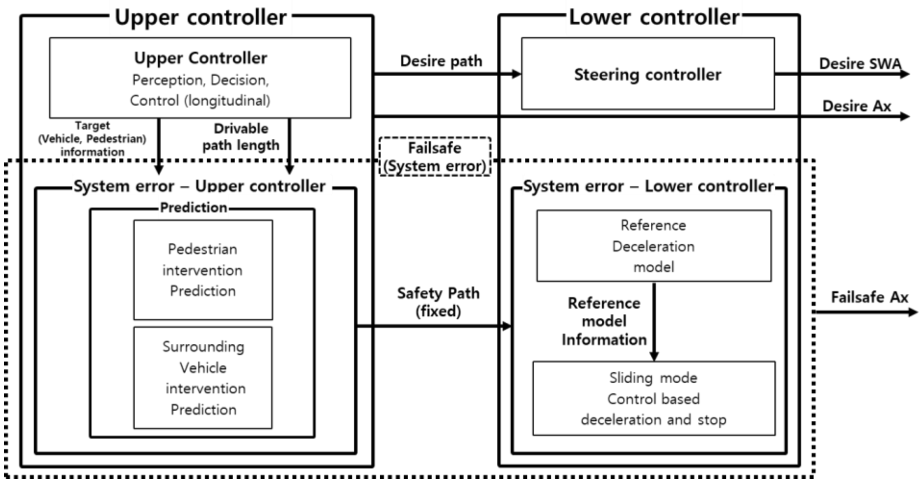


Figure4. Failsafe hardware concept diagram

mode control based deceleration and stop algorithm will be performed.

<u>Methodology</u> in this section, mainly describe System error situation used algorithm. One is defining reference deceleration model another is sliding mode control based deceleration and stop algorithm. The reference deceleration model [1] was determined by the general driver deceleration data which considering driver safety and ride comfort. The first-integrated velocity model and secondary integrated station model were used to construct an algorithm for stopping at safe distances. Pictures and formulas for longitudinal acceleration model, a longitudinal velocity model, and longitudinal distance model. V_x is initial velocity, a_m is maximum used deceleration, $\theta\,(\theta=t/t_d)$ is time ratio, t_d is deceleration time, m is a model variable parameter, r ($r=\frac{(1+2m)^{2+\frac{1}{m}}}{4m^2}$) is model parameter. Define a time-varying sliding surface $S(t)$ by the scalar equation $s(x;t)=0$, where $s(\mathbf{x};t)=e\cdot\left(\lambda+\frac{d}{dt}\right)^{n-1}$ and λ is a strictly positive constant. In this controller n =2 and he problem of keeping the scalar $s(t)$ at zero can be achieved by choosing proper control input u, the outside of $S(t)$, $\frac{1}{2}\frac{d}{dt}s(t)^2\le-\eta\left|s(t)\right|$ and let equation $s(\mathbf{x};t)=0$.

$$e(t)=S_{ref}(t)-S_{vehicle}(t) \tag{1}$$

$$s(t)=\dot{e}(t)+\lambda\cdot e(t) \tag{2}$$

$$V(s(t))=\frac{1}{2}s(t)^2 \tag{3}$$

In (1) $e(t)$ is an error between the reference station and vehicle station. (3) is Lyapunov function. Differentiating the Lyapunov function

$$\dot{V}(s(t)) = s(t) \cdot \dot{s}(t) \tag{4}$$

For a stable system, the derivative of the Lyapunov function should be negative.

$$\dot{V}(s(t)) = s(t) \cdot \dot{s}(t) = -K \cdot |s(t)| < 0 \tag{5}$$

$$\therefore \ \dot{s}(t) = -K \cdot tan(s(t)) \tag{6}$$

$$\dot{s}(t) = \ddot{e}(t) + \lambda \cdot \dot{e}(t) = -K \cdot atan(s(t)) \tag{7}$$

$$u_{eq} = a_{x,ref} - \lambda \cdot \dot{e}(t) - K \cdot atan(s(t)) \tag{8}$$

design (2) sliding surface. Design sliding surface and calculate control input (8) tracking sliding surface. Control input u_{eq} is a longitudinal acceleration to vehicle SCC module.

<u>Vehicle SCC (Smart Cruise Control) module description</u> SCC (Smart Cruise Control) module is the ADAS system of Hyundai Motor Company. Through the communication operation, longitudinal acceleration, which is the control input put into the SCC module. SCC module is a module that considers safety and ride comfort of drivers. If longitudinal acceleration or deceleration is inserted into the module, the actual input value and vehicle reacts has a time delay. To analyze the characteristics of the delay conducted SCC module delay test. The test method verifies the characteristics of the SCC module by inserting the deceleration value into the module as input during vehicle accelerates and cruising.

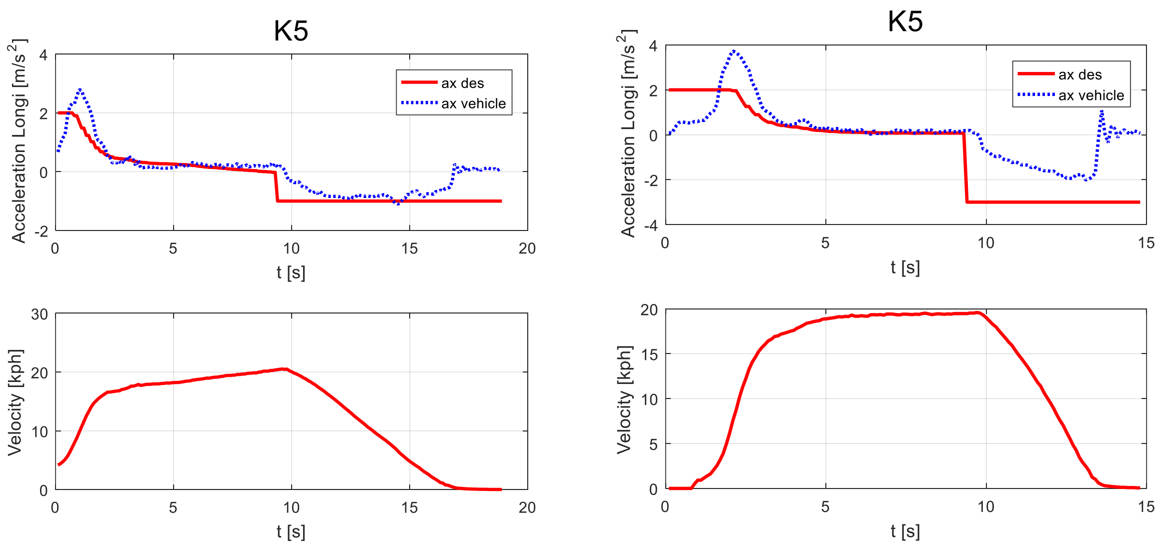
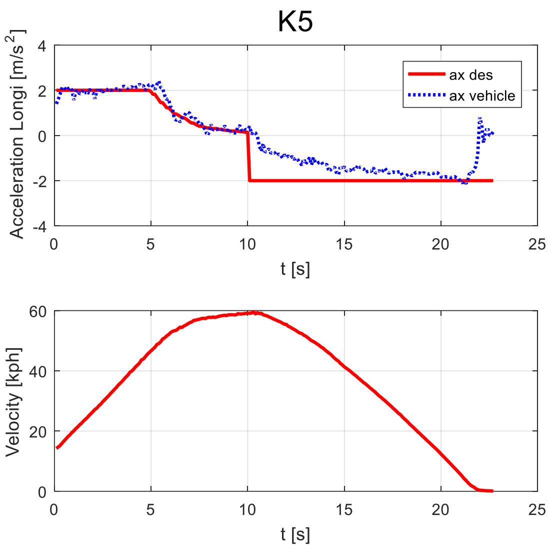


Figure5. K5 deceleration test ($-1m/s^2$***, 20kph)*** ***K5 deceleration test (*** $-3m/s^2$***, 20kph)***



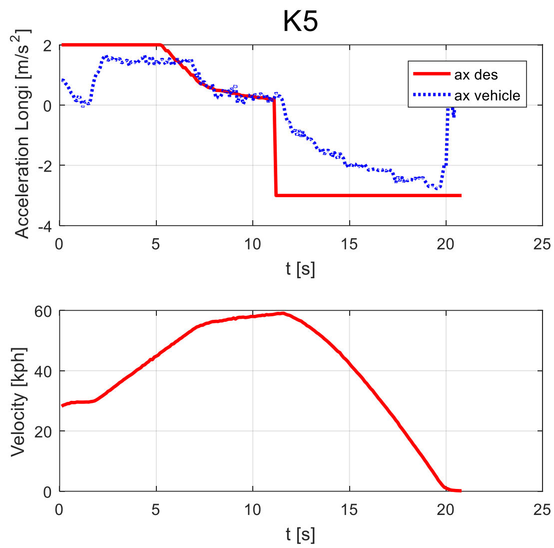


Figure6. K5 deceleration test ($-2m/s^2$ ***, 60kph)*** ***K5 deceleration test (*** $-3m/s^2$ ***, 60kph)***

If the reference model referred to in chapter 'Methodology' is inserted directly into the vehicle SCC module, it can be safely stopped within the specified distance of a simple configuration without the use of other control methods. Therefore, the output of the reference station and reference velocity utilized as control input. As a result, the problem of delay in SCC module extension time resulted in a value different from the value of the reference model to the output of the vehicle. The following chapter is the result of multiple experiments and test data showing that the SCC module has the nonlinear characteristic.

As mentioned above, control inputs were applied in several situations to experiment with nonlinear characteristics of SCC module. The test scenario is set as follow. 1. 20km/h (minus one to minus five) deceleration to stop 2. 40km/h (minus one to minus three) deceleration to stop 3. 60km/h (minus one to minus three) deceleration to stop 4. Acceleration test

K5 vehicle deceleration test for check SCC module delay. Test content contains constant deceleration from $-1m/s^2$ to $-3m/s^2$ when vehicle velocity close to 20 km/h and 60km/h. From test get a conclusion about SCC module delay as follow. First, module exists time delay about 0.1second to 0.5second. Second, module deceleration control input is not severe so couldn't reach command input . In conclusion, the SCC module exists time delay and nonlinear model characteristic.

<u>Sliding Mode Control based deceleration vehicle test</u> For the failsafe control deceleration and stop vehicle test, the following methods were used to conduct the test. The whole vehicle test was conducted in autonomous mode, from beginning to end the experimental scenario was planned and conducted in low-speed area of 20km/h and 30 km/h. Figure7 shows that the vehicle has been tested on autonomous mode from stop → accelerate → stops. The first figure in Figure7 shows the vehicle accelerating to ACC mode up to 30 km/h and the sliding mode control based algorithm operating when failure occurred. The second figure is a comparison of the longitudinal acceleration of the vehicle and the control input (longitudinal acceleration) into the vehicle SCC module.

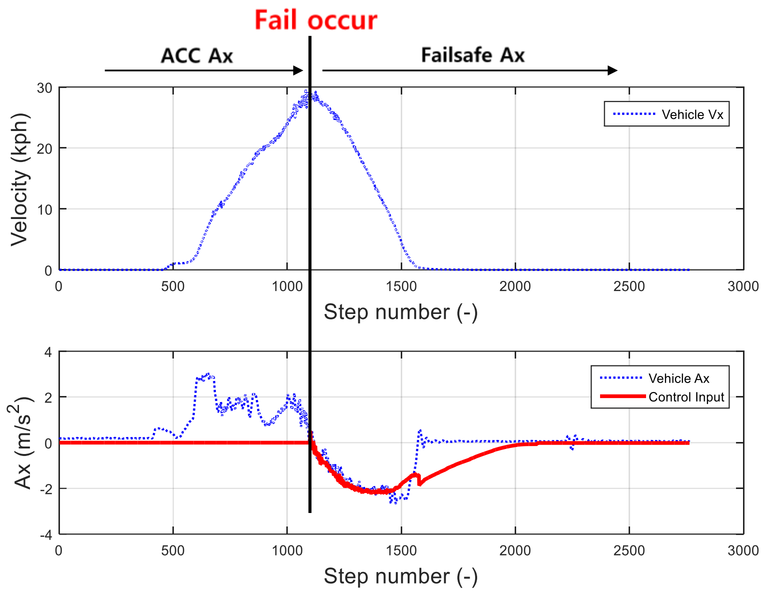


Figure7. Vehicle test scenario – Acceleration to stop

VEHICLE TEST RESULT

The fail-safe module described above chapter is applied to the autonomous vehicle as Figure8. As described in Figure8, a number of algorithm and method have been applied to the actual autonomous vehicle. The alarm system has been constructed to allow the driver to recognize the warning situation in autonomous vehicles. In perception part, 1) Internal CAN communication error in the vehicle, 2) CAN value holding error (for multiple CAN channels), 3) sensor hardware error. These error warning system has been constructed to alert the driver. The proposed automated driving control algorithm is evaluated through computer vehicle tests. In order to evaluate the proposed algorithm on a real test vehicle, Hyundai-Kia Motors K5 is used as a test vehicle platform. Figure 5 shows the test vehicle configuration. The proposed algorithm has been implemented on "dSPACE Autobox", which is used for the real-time application and equipped with a processor board. The hardware components mentioned above communicate through a CAN bus.

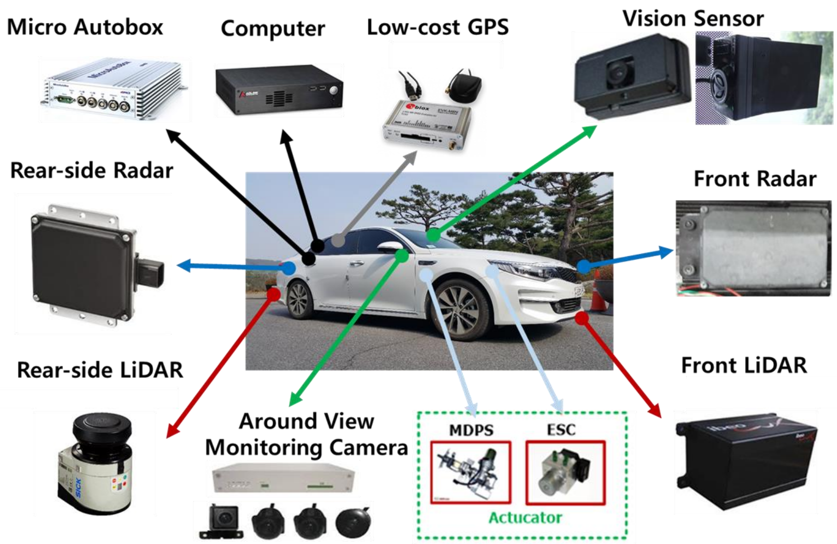


Figure8. Autonomous vehicle hardware configuration

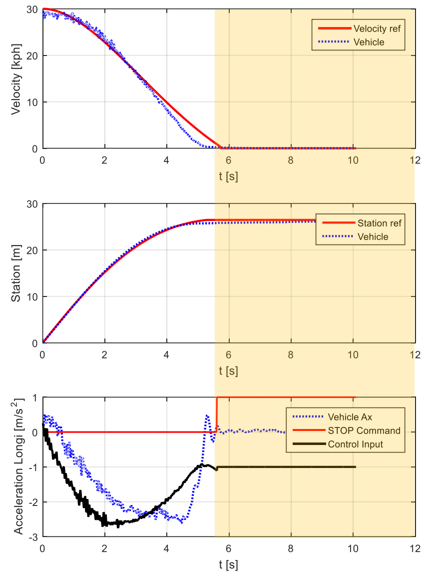


Figure9. Vehicle test result – (a) Velocity (b) Station (c) Vehicle and Control input

Figure9 is vehicle test result near 30km/h. (a), (b) and (c) are respectively the vehicle longitudinal velocity and reference model velocity profile, vehicle station and reference model station, vehicle acceleration and control input, the experiment result shows that the sliding surface follows well through the control input. The yellow section addresses overload problems on SCC modules rather than algorithmic stops and consists of stopping with constant deceleration as the speed decreases for module safety.

CONCLUSIONS

In this paper, in order to meet the requirements of autonomous driving phase proposed by SAE International, the hardware configuration was made to ensure that the driver could perform the autonomous vehicle task without driver proper intervention. In detection part, hardware (Actuator, Sensor, CAN signal, Upper controller, Lower controller) and module (Steering, Throttle/Brake, Lidar, Radar, GPS, CAN signal, CAN status, Chassis CAN) based failsafe diagnosis method and algorithm were proposed to detect fail situation. In decision and control part, when a failure of an autonomous vehicle is diagnosed and no driver intervention was detected, autonomous vehicle failsafe phase is a move to system error in figure4 in the phase of the system error (lower controller), reference station model and reference velocity model was calculated in real-time. Sliding mode controller based deceleration and stop algorithm tracking designed sliding surface. The effectiveness of the proposed automated driving fails situation deceleration algorithm has been evaluated via test-data based simulations and vehicle tests. From the results, it has been shown that the proposed algorithm can provide the robust performance in low speed (20,30kph) condition.

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